

Introduction: One of the important outstanding goals of lunar science is understanding the bombardment history of the Moon and calibrating the impact flux curve for extrapolation to the Earth and other terrestrial planets. The "terminal lunar cataclysm," a brief but intense period of bombardment about 3.9 billion years ago, is of particular scientific interest. Radiometric dating of lunar impact-melt rocks forms the backbone of the lunar cataclysm hypothesis. A histogram of precise age determinations of impact-melt rocks shows the characteristics of the classic formulation of the lunar cataclysm hypothesis: a sharp peak at 3.9 Ga, a steep decline after 3.9 Ga perhaps only 20-200 Myr long, and few rocks of impact origin prior to ~4.0 Ga [1-3]. The paucity of impact-melt rocks older than 3.9 Ga has been variously interpreted as evidence that there was a low flux of impactors prior to ~3.9 Ga, creating few impact melt rocks [2], that the early impactor flux was so high that the lunar crust was reset and/or destroyed (the "stone wall" effect) [4], or that the dated samples may all be related to a single basin-forming event, Imbrium [5]. If the early lunar flux were much lower, then the apparent spike in impact rate would be a true "cataclysm." If the flux were much higher, than the increased flux could be viewed as simply a bump or inflection on a generally declining post-accretionary impact rate.

Mass constraints on the amount of material needed to create the large lunar basins appears to support a low pre-Nectarian flux [6], and the population of planetesimals remaining from planetary accretion would have been insufficient to produce as many basins as late as Imbrium, Serenitatis, and Nectaris [7]. Instead, insights gleaned from our improved understanding of giant planet formation and migration in planetesimal disks suggest that the Jovian planets experienced a late, sudden instability as they crossed some mutual resonance. This triggered a rapid depletion of the trans-Neptunian planetesimal disk and caused an acceleration of the migration of Jupiter and Saturn, which in turn destabilized the majority of the asteroids in the main belt. The "Nice model" built on this idea not only explains the main characteristics of the impact spike in terms of delay, intensity and duration, but also the current orbital architecture of the giant planets, the existence and the orbital distribution of many populations of small bodies (trojans, KBOs, satellites) [8-10]. This class of dynamical models, that invokes secular sweeping of the asteroid main belt via resonances, has been bolstered by work

on the size-frequency distribution of lunar craters mirrors that of the main belt [11]. The responsible impactor population, and the dynamics of its delivery, plays an important role in determining whether the impact flux history of the Moon should map onto the other terrestrial planets.

The lunar cataclysm hypothesis continues to be tested. Indeed, the top three science goals articulated in The Scientific Context for the Exploration of the Moon (SCEM) [12] relate to placing better constraints on the lunar impact flux. Because of the fine detail gleaned in terrestrial labs from existing samples, the level of precision needed to address some of the outstanding questions related to the cataclysm depends on sample return. However LRO could assist in meeting these goals in important ways:

(SCEM 1a) Test the cataclysm hypothesis by determining the spacing in time of the lunar basins. There is little recognizable pre-Nectarian terrain on the Moon for crater counting, stratigraphy, or association with rock ages. However, the timing of the large Imbrian-era basins can be constrained by using LRO high-resolution images to provide targeted crater counts of undisturbed ejecta surfaces from Orientale, Imbrium, Serenitatis, and Nectaris, as well as Imbrian-era farside basins. Identification and mapping of extant melt sheets in nearside basins such as Nectaris and in farside basins would be important in guiding future missions to sample such lithologies.

Another possibility for putting age constraints on ancient surfaces may be improved crater counting on the oldest basalt flows. In turn, stratigraphic relationships between such ancient basalt flows and basin ejecta may help bound basin formation ages. Some of these flows have been identified on the eastern limb by crater counting [13, 14]. Others may be identified based on their mineralogical or elemental affiliation with ancient basalt samples in our collection, such as the high-Al basalts and lunar meteorite Kalahari 009 [15-17]. In particular, farside flows may hold important clues. Model ages of mare deposits on the lunar farside using crater frequency distributions in 10 m/px images obtained by Kaguya's Terrain Camera identified an ancient basalt flow in Mare Nishina, at ~3.85 Ga.[18].

(SCEM 1b) Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin, the South Pole-Aitken (SPA) basin. The SPA basin, with a diameter of 2000 km, is the stratigraphically oldest lunar basin and probably created more impact melt than all other lunar craters combined.

Endogenous impact melt probably still resides on the basin floor and could be directly sampled by a robotic mission. Before that time, however, higher-resolution images to provide targeted crater counts on ejecta of basins within SPA would help bound the SPA formation age and provide constraints on the impact history provided by a scoop sample. Remote sensing of possible sample collection sites is also crucial to help determine the regional geologic context of future returned samples.

(SCEM 1c) Establish a precise absolute chronology. It is important to understand the inflections and changes in of the lunar flux throughout time so that we can judge whether a period, such as the Cataclysm, is truly anomalous. Are age-correlated changes in the apparent lunar crater size-frequency distribution due to of erasure of small craters or due to evolution of the production function? How do changes in the lunar crater size-frequency distributions reflect the impactor populations responsible for creating them? Higher-resolution images providing targeted crater counts on selected ejecta facies, such as Copernicus and Tycho, will be able to be correlated with radiometric ages. The very young end of the lunar flux curve can be examined by comparing new remote sensing data sets with Apollo-era data sets to detect formation of new craters.

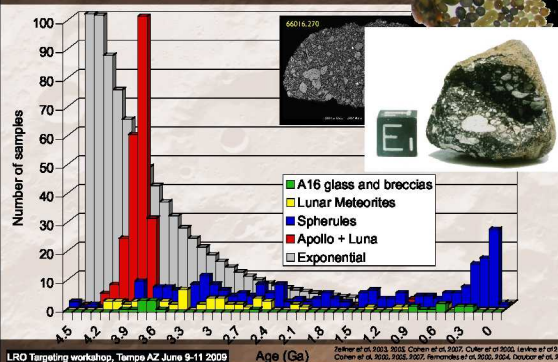
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The Lunar Cataclysm And How LRO Can Help Test It

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Lunar impact ages

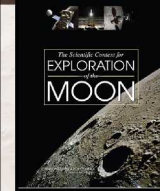


The Lunar Cataclysm

- Many Apollo 14, 16, 17 rocks crystallized at 4.5 Ga but experienced Pb loss at 3.9 Ga Tera et al (1974)
- Subsequent Rb-Sr and Ar-Ar ages corroborate the large number of ~3.9 reset or disturbance ages
- Impact-melt sample groups tied to individual impact events based on major, minor, and trace elements, geologic interpretation
- Elements of the classic cataclysm:
 - Widespread lunar metamorphism by impact
 - Created at multiple large basins in <0.2 Gyr
 - Resurfaced 80% of the lunar surface
- An important time in Earth-Moon system

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High-priority science goals



- 1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins.
- 1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).
- 1c. Establish a precise absolute chronology.
- 4a. Determine the compositional state (elemental, isotopic, mineralogical) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.
- 3a. Determine the lateral extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.
- 2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.
- 2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.
- 8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.
- 2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.
- 3b. Inventory the variety, age, distribution, and origin of lunar rock types.
- 8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.

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SCEM 1a. Test the cataclysm hypothesis by determining the spacing in time of the lunar basins

- Little recognizable pre-Nectarian terrain on the Moon for crater counting, stratigraphy, or association with rock ages
- LRO high-resolution images could provide targeted crater counts of undisturbed ejecta surfaces from Orientale, Imbrium, Serenitatis, and Nectaris, as well as Imbrian-era farside basins
- Identification and mapping of extant melt sheets in nearside basins such as Nectaris and in farside basins will be important in guiding future missions to sample such lithologies

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SCEM 1a. Test the cataclysm hypothesis by determining the spacing in time of the lunar basins

- Stratigraphic relationships between ancient basalt flows and basin ejecta may help bound basin formation ages
- Targets = improved crater counting on oldest basalt flows
 - eastern limb by crater counting (Hiesinger et al. 2000, 2003)
 - high-Al basalts possibly TBD by M3
 - ancient basalt flow in Mare Nishina dated to ~3.85 Ga using 10 m/px images from Kaguya's Terrain Camera (Haruyama et al. 2009)

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SCEM 1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin, SPA

- The SPA basin is the stratigraphically oldest lunar basin and probably created more impact melt than all other lunar craters combined.
- Targeted crater counts on ejecta of basins within SPA (e.g. Apollo, Ingenii, Poincaré) help bound SPA age and provide constraints on the impact history provided by a scoop sample.
- Imaging of possible sample collection sites is also crucial to help determine the regional geologic context of future returned samples.

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SCEM 1c. Establish a precise absolute chronology

- Understand the inflections and changes in lunar flux to be able to judge whether a period, such as the Cataclysm, is truly anomalous
 - Are age-correlated changes in the apparent lunar crater size-frequency distribution due to of erasure of small craters or evolution of the production function?
 - How do changes in the lunar size-frequency distributions reflect the impactor populations that created them?
- Target: crater counts on benchmark crater ejecta (Copernicus, Tycho) to correlate with absolute ages
- Target: Change detection since Apollo to understand the very young end of the lunar flux curve

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Human outpost / sortie support & planning

- OSEWG and other groups have been planning candidate science scenarios to help derive CxP architecture requirements and capabilities
- Several scenarios intended to address Cataclysm issues (Schrodinger, Nectaris sortie)
- Strategy: Target areas that will aid traverse planning to more accurately plan routes (=distance), realistic goals (steep slopes, boulders), maximize success
- Issues: These areas are large to immense; impossible to completely cover. But small areas would validate/inform interpretation of lower-res imaging of adjacent areas.

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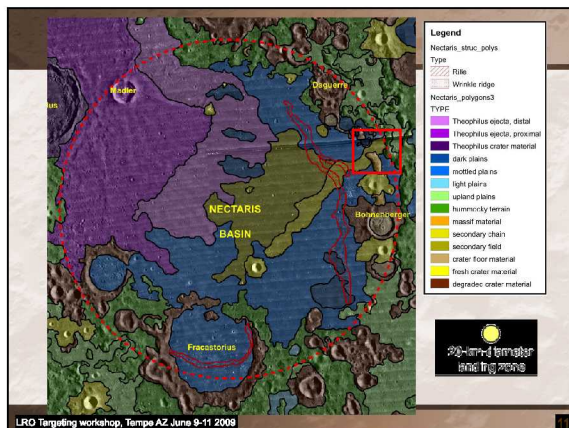
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Sortie scenario: Nectaris Basin Edge

- Determining Nectaris Basin age, establishes age/ structural relationship between basin formation and volcanic activity.
- Samples portions of exposed highland basin massif, basin floor, and mare basalt fill.
- Supports Goals A-1, 2, 3, 4, 5, 6, 8, B-1
- Petro et al LPSC 2009, Bleacher et al LPSC 2009

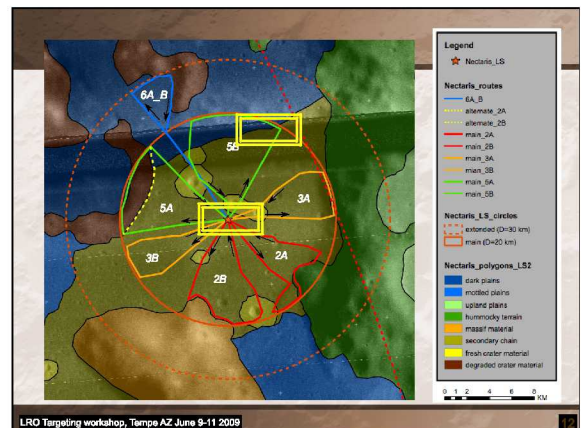
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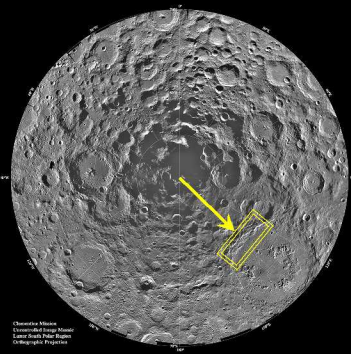
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Outpost-based EVA: Schrodinger Basin



- Second-youngest impact basin
- Intersects inner rings of the South Pole-Aitken (SPA) basin.
- Inner ring might contain indigenous SPA materials from depth
- Volcanic units, deep fractures, etc.
- ~500 km from outpost site on a direct route
- Is the interior accessible?
- Kohout et al LPSC 2009
- Clark et al LPSC 2009

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Summary / Recommendations

- How LRO can help test the Cataclysm: targeted RS used for improved crater counts, identification/context of sampling areas, and support for human activities
 - Nectaris and Schrodinger Basin sortie areas
 - Interior/edge of farside basins
 - In-SPA basin ejecta (suggest Apollo, Ingenii, Poincaré)
 - Possible sample collection sites within SPA if teams provide them
 - Oldest basalt flows (Hiesinger)
 - Benchmark crater ejecta (Copernicus, Tycho)
 - Change detection (Robinson)

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